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The Valhall Waterflood Evaluation: A Decision Analysis Case Study

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Abstract

This paper is based on the work of a multi-disciplinary team, formed to evaluate the economic potential, with associated risks, of waterflooding the Valhall Field. The evaluation includes selection of facility concept and quantification of probabilistic project economics. The decision analysis is performed using economic models, tornado diagrams, decision trees and monte carlo simulations and presented as cumulative probability functions. The paper outlines the evaluation process from screening to selection of final concept and discusses uncertainties, risks and upside potential associated with waterflooding the Valhall chalk reservoir. This decision risk analysis process gives a simple method for ranking project uncertainties and helps the team to focus on key project drivers which lead to a better understanding of project risks and potential risk mitigation.

Introduction

The Valhall field is a high porosity naturally fractured chalk reservoir located 290 km offshore, in the southwest corner of the Norwegian North Sea. The field was discovered in 1975, with first oil in October 1982. Production drilling is currently ongoing from 2 drilling rigs, and is expected to result in peak production from Valhall in 1999 from a total of 49 wells.

The Original Oil In Place is approximately 2350 mmstb, located in two main reservoir layers, the Tor formation and the Hod formation. Owing to the weakness of the high porosity chalk and the very low original net stress, the Tor formation exhibits exceptional drive energy through pore collapse and compaction.[1,2,3] The expected field recovery factor under primary depletion is close to 25%.

In 1989, the reservoir pressure declined below the bubble point in the central areas of the field. A single well water injection pilot was then implemented to give critical information on the viability of water injection. Three years of pilot operation and subsequent analysis of results gave valuable experience and information for evaluating the potential of a full field waterflood at Valhall[4].

Although water injection has been studied repeatedly for the Valhall field, it has never been found economically attractive. This is mainly due to the very efficient recovery achieved through pressure depletion, which is essentially lost under a pressure maintenance scheme.

In 1996 a multi-disciplinary study team was formed with the objective of evaluating the best economic concept for waterflooding the Tor formation.

The Study Process

The project had the following main objectives:

- Identify the most attractive development option.
- Assess economic potential.
- Recommend future actions on Waterflood.

Project risk and upside potential were identified as key decision criteria. The process of decision risk analysis was divided in to four steps (Figure 1):

Step 1: Framing the problem. The project team defined the problem and boundaries. The project risks, dependencies, strategies and development options were identified and models for the project evaluation were established.

Step 2: Deterministic Analysis. Having framed the problem, it was important to screen the parameters. This enabled the team to focus and target resources on the key project drivers.

Step 3: Probabilistic Analysis. The project uncertainties were modeled. The output was a probability distribution and expected value for each of the development options.

Step 4: Evaluation Appraisal. The complex probabilistic model required verification and quality control. Assumptions and validity of the model needed confirmation. Insights such as value of information and impact of risk mitigation measures were calculated.

Framing the Problem and Screening the Options

Initially, the project team was faced with numerous alternatives for the size and placement of the water injection facilities:

- Modification of existing Valhall platforms (with and without additional well slots)
- New platform (with and without well slots)
- Subsea injector wells with facilities placed on existing Valhall complex
- Sharing of facilities with neighboring installation
- Lease of a dedicated jack-up rig
- Various combinations of options above

A structured method was needed to screen these alternatives and narrow down on the key options. The team developed high level design and capital cost estimates for these facility options based on a "building block" approach. Cost estimates were developed separately for each of the main components:

- Slots and wells
- Seawater treatment
- Produced water treatment
- Injection system
- Deck area
- Marine operations

The components could then be easily assembled to represent the different scenarios. Production profiles and operating cost estimates were also developed for each of these options and screening economics were run. This resulted in the rejection of 4 options, and the selection of two options for further assessment;

- Build a new dedicated platform for waterflood
- Modify existing facilities for waterflood

These cases represented a 'large' and 'small' waterflood and a well-known dilemma between,

- high up front expenditure with large upside potential, and
- small capital exposure with limited upside potential.

The team also investigated if phasing the development over time would reduced the downside and thereby improve the expected value over the non-phased options.

Decision Hierarchy. An important step in structuring the problem was to identify the main decisions to be made during this part of the project. The decision hierarchy (Figure 2) is a simple, yet powerful tool to distinguish between three types of decisions:

- Policy: Decisions taken as given
- Strategy: Decisions to be focused on
- Tactics: Decisions to be deferred for now

This helped focus the study efforts on the key decisions.

Strategy Table. Having developed the economic model, the development options or 'strategies' were identified. These were presented in a 'strategy table' as shown in Table 1.

Economic Model, Influence diagrams and Input Data. The economic model was required to accurately handle expenses, revenue, tax, cash flow and economic indicators. It needed to be flexible in dealing with Real Term (RT) and Money Of the Day (MOD) conversions. In addition it needed deterministic as well as statistical options.

Influence diagrams (Figure 3) were used to map how parameters influence the result and guide the building of the economic model. The influence diagrams were established in a series of team meetings and during this process it built awareness within the team of how factors impact and relate to the problem.

Having developed a clear understanding of the problem the ranges in input data were established. An iterative approach is often required to do these estimates. Very often the most likely value is well described, but less attention has been paid to low (10/90) and high (90/10) estimates. In an iterative approach, the sensitivity analysis established the key variables. Resources would then focus these variables as they controlled the main uncertainty of the problem. Less accurate estimates are usually acceptable for variables with less impact on the result.

Deterministic Analysis

After having framed the problem and formulated possible development strategies, the model was used to evaluate the economic merit of each of the strategies.

A high level assessment of the likely variability of each parameter and it's influence on the project economics were then performed by varying one parameter at a time, from low, base, to it's high value.

Tornado Chart. The results of the sensitivities are visualized in a Tornado chart (Figure 4a). The parameters are sorted from top to bottom based on total impact on the project economics*. The parameters are centered on their base value, while the horizontal bars indicate how the uncertainty in each parameter impacts the total project economics.

The initial Tornado chart for the Valhall waterflood project shows that the uncertainty in the production response has the largest impact on the project economics. This parameter alone could swing the project NPV from a reasonable investment to a relatively large loss. Similar Tornado charts were developed for all the alternative development strategies.

Business Drivers. Based on the sensitivity results and the Tornado Chart analysis, the main business drivers were readily identified. As a rule of thumb, a comparison of the square of the length of the horizontal bars in the Tornado chart gives an estimate of the relative impact of the parameters in the probabilistic analysis. For the waterflood project the production response is approximately nine times more important than the second ranked parameter in describing the total variability in the project (Figure 4a). This guides the selection of which and how many business drivers are needed to adequately describe the project risk.

For the Valhall waterflood, production response, injection well operating cost (well OPEX) and injection well drilling and completion cost (well CAPEX) were the three main business drivers, with production response being by far, the dominant parameter.

Refinement of Estimates. The identification of business drivers also provided a focus for the effort to minimize project uncertainty. Detailed analysis of the business drivers, resulted in refined value estimates and important insight into the factors that determines the success or failure of the project. The refinement of the ranges for the business drivers is a critical step in ensuring quality input to the subsequent probabilistic analysis.

The decision risk analysis process (Figure 1) can also be effectively used in developing refined estimates for each of the business drivers. For instance, for the waterflood project, the production response is the dominating business driver. By applying the decision risk analysis process, the production response can be broken down to a subset of reservoir parameters with associated uncertainty ranges. Through sensitivity studies, the impact of each parameter can be quantified and ranked by use of a production Tornado Chart.

* All financial numbers in this paper have been manipulated to avoid confidentiality conflicts.

The effort to refine the estimated value ranges for the parameters in Figure 4a is limited to the main business drivers. Further refinement of the estimates for the lower ranked parameters may give better estimates, but is not likely to impact the final decision or significantly reduce the variability in the project economics. For the waterflood project, the focus on business drivers reduced the study effort from the original eight factors to four factors, of which the production response was the most critical to resolve.

Production Response. With the production response identified as the critical business driver, a detailed analysis was performed to improve the estimate for the production response with respect to both base value and variability. With the many factors influencing the production response, it was decided to use the decision risk analysis process as a tool to ensure a systematic approach in refining the estimate.

A decision hierarchy analysis was performed to determine the scope of the analysis, and an influence diagram was created to identify the most important parameters influencing the production response. Ranges were then estimated for each of the parameters and a series of sensitivities were performed. The key drivers for the production response were identified and the need for further refinement assessed.

The initial estimates for low, base and high values for the production parameters were based on available data, experts' estimates, results from previous studies and available benchmark and analog data. The sensitivity analysis was performed with a black-oil full field reservoir model. The production Tornado Chart (Figure 5a) summarizes the results of the first set of sensitivities. Gas/Oil relative permeability, water rock interaction and residual oil saturation are the three top parameters impacting the production response. However the lower half of the Tornado Chart also includes parameters that have a significant impact on the production response.

Given the critical impact of the production response on the total project economics it was decided to verify and refine the estimates for the parameters influencing the production response, with the aim to ensure that the decision risk analysis was based on quality estimate for the main business driver.

Residual Oil Saturation (Sorw). The effectiveness of the waterflood sweep efficiency, both microscopic and macroscopic, were considered to be crucial to the production response, even though it was only ranked third in the first iteration of the Tornado chart (Figure 5a). Through reassessment of two and three phase special core analysis and appropriate pseudo relative permeability functions, the initial uncertainty range for the Sorw was considered to be too narrow and consequently the impact on the production response was under estimated.

The refined range for expected Sorw was 0.13 - 0.25. This gave a downside of -33% and upside of +10% compared to the base case waterflood incremental reserves.

Gas-Oil Relative Permeability. (G/O RelK). The primary target area for the Valhall waterflood is the central area of the field, where the reservoir thickness is best, and permeability higher due to extensive natural fracturing of the chalk. This area is very depleted and a secondary gas cap is forming. Waterflooding of this area will lead to trapping of gas, and significant gas losses are expected as a result of the planned waterflood.

In an attempt to narrow the uncertainty range on the gas losses, all available two and three phase relative permeability data was reassessed. The data indicated that there was significant uncertainty related to gas, water and oil mobility in the presence of gas[5]. In addition, the gas saturation in the reservoir was also considered to be uncertain.

The gas loss remains as one of major uncertainties in defining the waterflood production response. The high gas loss estimate reduces waterflood reserves by 15%, while the low gas loss estimate increases the waterflood incremental reserves by approximately 19%.

Rock Compaction. The most striking reservoir property associated with the Valhall field is the very high rock compaction and rock compressibility that is observed during pressure depletion of the field. The rock compaction has been measured through numerous laboratory stress tests, but is modified in the history matching process to match well observations of reservoir pressure. The rock compaction is triggerd by reduction in pore pressure and therefore most critical to the performance of the current pressure depletion strategy, and less critical to the pressure maintenance scheme represented by the waterflood project. Rock compaction is important for the waterflood evaluation, as the evaluation is based on the incremental performance of the waterflood strategy over the current strategy.

With the rock compaction curves being a history match parameter there exists several viable predictions for future rock compaction. Based on an assessment of the likely range in rock compaction scenarios, the downside estimate for the waterflood incremental recovery was estimated to -8% compared to the waterflood base case reserves, while the upside case was +11%.

Injectivity. The Valhall permeabilities are typically 1-5 mD, with significantly higher permeabilities in areas where open natural fractures are present. Injectivity during waterflooding is therefore an important issue, and a concern in the areas outside the fractured central areas. Due to the relative thin formation in the flank areas (30-100ft) horizontal injectors are planned. It is also considered necessary to inject above the formation parting pressure[6] to achieve the required water injection rates. This raises issues related to injection profile control. Injection of produced water adds additional uncertainty to the expected injectivity[7]. Considering all of the factors above, a range of horizontal well completion efficiencies were defined to represent uncertainty in injectivity.

The impact on waterflood incremental reserves were quantified to -15% for downside case, and +2% for the upside case, relative to the waterflood base case. The financial impact of the injectivity uncertainty is somewhat higher than the reserves impact, as higher injectivity gives an acceleration effect in addition to the added reserves and vice versa for downside case.

Original Oil In Place (OOIP). Due to imaging problems caused by a gas cloud in the overvurden over the central parts of the Valhall field, the OOIP is uncertain. The variability in the OOIP estimate was based on a recent geological reassessment of the field. The OOIP was initially thought to be a parameter that would require extensive analysis before a refined estimate could be provided. Sensitivity analysis on the initial estimates did, however show that the OOIP played a minor role in describing the uncertainty in the waterflood production response.

The initial estimate of the uncertainty in OOIP was +/-10% in the areas targeted for water injection. The downside case was estimated to -9% and the upside case to +4% relative to the base case waterflood incremental reserves.

Water Induced Permeability Increase (WIPI). One of the novel effects associated with the Valhall waterflood is an spontaneous water induced rock compaction with associated increase in permeability[8]. The spontaneous rock compaction has been confirmed in core experiments, while the permeability increase is observed in field tests.

The impact on waterflood production response was initially estimated based on very simplified methods. In order to refine the estimate, core data and PTA data from the pilot injection test was reassessed. Work was also initiated with the reservoir simulation software vendor to incorporate water saturation versus permeability and water saturation versus pore volume relationships in the reservoir model.

The final base case estimate includes a component of improved permeability, while the low case represents no permeability enhancement. As a result of the improved ability to model this effect, the estimated impact of WIPI changed significantly compared to the initial estimate (Figure 5a and 5b).

Directionality. The permeability in the Tor formation of the Valhall field is locally enhanced by open fractures serving as fluid conduits. The preferential direction of these open fractures will impact the waterflood production response. No geological work was performed on this parameter, as even an extreme degree of directional permeability gave only a marginal difference in waterflood response.

Final Production Tornado Chart. Based on the above parameters, an updated Tornado chart for the production response was generated (Figure 5b). This changed the ranking and the impact of the reservoir uncertainties compared to the initial Tornado chart.

Well OPEX. Solids production and well collapses cause high well operating costs at Valhall. Historically, the well life of new wells is limited to an average of 7 years, before a complete redrill needs to be performed. The main driver for the well OPEX is well life. Well lives of 3.5, 7 and 12 years were assumed for the low case, base and high estimates for well OPEX. The well OPEX was divided into injection well OPEX and production well OPEX.

No refinement of the actual re-drill costs were considered necessary, as this is well established through statistical data on historical performance.

Drilling CAPEX. The first iteration on the drilling cost was performed using a typical well cost for an injection well independent of well location. For the refinement, drilling time estimates were prepared for each of the injection wells based on preliminary reservoir targets. The drilling cost was also revised to reflect drilling performance of the ongoing drilling and predicted trends in daily rig rates.

Final Project Tornado Chart. Based on the refined estimate ranges, the total project Tornado chart was updated (Figure 4b). Through the analysis of the business drivers, the confidence and understanding of the key parameters impacting the project was improved significantly, ensuring quality input to the probabilistic analysis.

Probabilistic Analysis

The deterministic analysis focused on quantifying the impact each parameter has separately on the project economics. In the probabilistic analysis, all parameters are varied simultaneously, and the impact of the combined parameter uncertainty in the project is quantified as a economic value with an associated probability of occurring. The Expected Values (EV), or the probability weight average outcome, is also calculated.

Decision Tree. A probabilistic model is based on a decision tree analysis. The four top ranked parameters identified from the tornado chart were used to construct a decision tree (Figure 6). The decision tree is then used to evaluate all possible outcome combinations with associated probability and Net Present Value (NPV) for each of the development options.

The parameters selected for the analysis were, production response, injector well OPEX, drilling CAPEX and producer well OPEX. The four selected parameters captured more than 98% of the total variance of the project.

The decision tree analysis was run for the following cases:

- New Platform 15 wells (NP 15)
- New Platform 11 wells (NP 11)
- Existing Platforms 5 wells (DP 5)
- Existing Platforms 5 wells followed by 6 additional wells 4 years after first injection (DP 5+6)

Cumulative Probability Curve. The results from the decision tree analysis are presented in the form of a cumulative probability curve, or a Expectation Curve[9] with NPV on the x-axis, and cumulative probability on the y-axis. By plotting the alternative waterflood strategies on the same plot, the potential risk and reward for each alternative can be assessed on a comparable basis (Figure 7).

Figure 7 shows the comparison between building a new platform with 11 or 15 well slots or modifying existing platformsfor the Valhall waterflood. The following can be concluded;

- All strategies have considerable risk, with approximately 50-70% chance of loosing money
- All options have negative expected value.
- NP15 has the best expected NPV, while DP5 has the lowest expected NPV.
- NP15 has considerable higher upside potential than the DP5, while the difference in risk is less pronounced.

Based on the probabilistic analysis, the new platform 15 wells option (NP15) was picked as the preferred development concept. This option has a slightly negative expected NPV, with significant risk of loosing more money. The upside potential of this case, encourages further analysis of the probabilistic results to explore possible risk mitigation with the aim of achieving a positive expected NPV.

Appraisal

In this phase the results of the probabilistic analysis were evaluated. The probabilistic analysis identified that all the strategies were associated with high risk and through evaluation of the probabilistic results, possible risk mitigation measures can be analyzed. The value of additional information was analyzed and the impact of phasing the waterflood development was evaluated, with the aim of identifying actions that would reduce the risk associated with the project.

Value of Information. The available tools gave us the possibility of evaluating the value of additional information. The uncertainties are assumed to be solved before the decision is made. If this gives a better NPV than the base case it represents the value of what the project might be willing to pay for this information. Figure 8 illustrates how perfect information on waterflood production response impacts the cumulative probability distribution. In this case, the value of eliminating the low production scenario can be calculated and decisions on additional testing or data gather can be made[9]. In real life information is rarely perfect, meaning that not all uncertainties are removed when gaining more information.

Phased Development. One way to gain relevant information is to phase the project (start small and expand if performance is favorable). Since most of the downside is due to production uncertainty, the effect of phasing the capital investment by delayed drilling until more reservoir data is gathered, was evaluated (Figure 9). The evaluation concluded:

- Phasing the investment does not increase the value of the project
- The NP phasing options requires most of the investment to be made up-front, thus limiting the minimization of the downside.

Preferred Concept

Based on the decision risk analysis evaluation the preferred concept can be summarized as follows:

- New Platform Bridge linked to existing Valhall Platforms
- Equipment to inject 210,000 barrels of water daily
- Equipment to treat 100,000 barrels of produced water daily
- 15 Well Slots
- Utility and safety equipment to support water injection, drilling and limited production.
- The design is based on re-injection of all produced water.

The project is expected to increase field reserves by approximately 75 mmboe, by injection of close to 800 mmbw over a 12 year period.

Conclusions

Based on the study, the following conclusions can be made;

1. The decision risk analysis was a powerful tool to identify key drivers that could impact project success.

2. The decision risk process helped the team focus their efforts on evaluating the key business drivers and thereby defer work that was not essential to the key decision.

3. The decision risk analysis highlighted the overall risks with the project and helped quantify how much money one would be willing to spend to reduce risks.

4. The process was successful in its main objective to select the preferred development concept, taking into account both technical and economical risk. The methodology facilitated selection on an equal comparison basis.

5. Based on the results from the decision risk analysis, a new water injection platform, bridge linked to the existing Valhall facilities was selected as the preferred development concept.

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References

1. Ruddy I., Andersen, M.A., Pattillo, P.D., and Bishlawi, M., "High Porosity chalk reservoir: a case study of Valhall field," JPT, July 1989, 741-746.
2. York, S.D., Peng, C.P., Joslin, T.H., "Reservoir Management of the Valhall Field, Norway, a high porosity, naturally fractured chalk formation," paper SPE 20992 presented at Europec, The Hague, Netherlands, Oct 22-24, 1990.
3. Powley, K.D., Peng, C.P., Ali, N., "Simulation of a North Sea Chalk Reservoir With Dynamic Rock And Natural Fracture Properties: Case Study of the Valhall Field", paper SPE 24914, presented 67th Annual Technical Conference and Exhibition, Washington, DC, October 4-7, 1992.

4. Ali, N., Alcock, T., "Valhall Field, Norway - The First Ten Years," published in "North Sea Oil and Gas Reservoirs - III", 25-40, Norwegian Institute of Technology (NTH), 1994. Published by Kluwer Academic Publishers.
5. Nordtvedt, J.E., Ebeltoft, E., Iversen, J.E., Sylte, A., Urkedal, H., Vatne, K.O., Watson, A.T.,"Determination of Three-Phase Relative Permeability from Flooding Experiments" paper SPE 36683 presented at 1996 Annual Technical Conference and Exhibition, Denver, Co, October 6-9, 1996.
6. Ali, N., Singh, P.K., Peng, C.P., Shiralkar, G.S., Moschovodis, Z., Baack, "Injection above-parting-pressure waterflood pilot, Valhall Field, Norway" paper SPE 22893 presented at SPE Annual Technical Conference and Exhibition, Dallas, TX, October 6-9, 1991.
7. Bodnar, D.A., Clifford, P.J., Isby, J.S., Lane, A.C., Loveland, R., Seymour, L.I., Urban, D.M., Schultz, M.S., Waltz, G.S., "First Horizontal Water Injectors in Prudhoe Bay Field, Alaska" paper SPE 35588 presentedat 1996 SPE Western Regional Meeting Anchorage, Alaska, May 22-24, 1996.
8. Cook, C.C., Andersen, M.A., Halle, G., Gislefoss, E.,Bowen, G.R.:"Simulating the Effects of Water-Induced Compaction in a North Sea Reservoir," paper SPE 37992 presented at SPE 14th Reservoir Simulation Symposium, Dallas, TX, Jun. 8-10, 1997.
9. Behrenbruch, P., Azinger, K.L., Foley, M.V., "Uncertainty and Risk in Petroleum Exploration and Development: The Expectation Curve Method", paper SPE 19475 presented SPE Asia-Pacific Conference, Sydney, Australia, Sept. 13-15, 1989

TABLE 1

STRATEGY TABLE FOR KEY DECISIONS			
Water Injection Rate	# of slots	Facility Design	Investment Phasing
120 mbwpd	None	Existing Complex	All at once
180 mbwpd	5	New Platform	5+6 wells (in 4 yrs)
210 mbwpd	5+6		11+4 wells (in 4 yrs)
240 mbwpd	11		
300 mbwpd	15		
	19		
	24		

Strategy #1

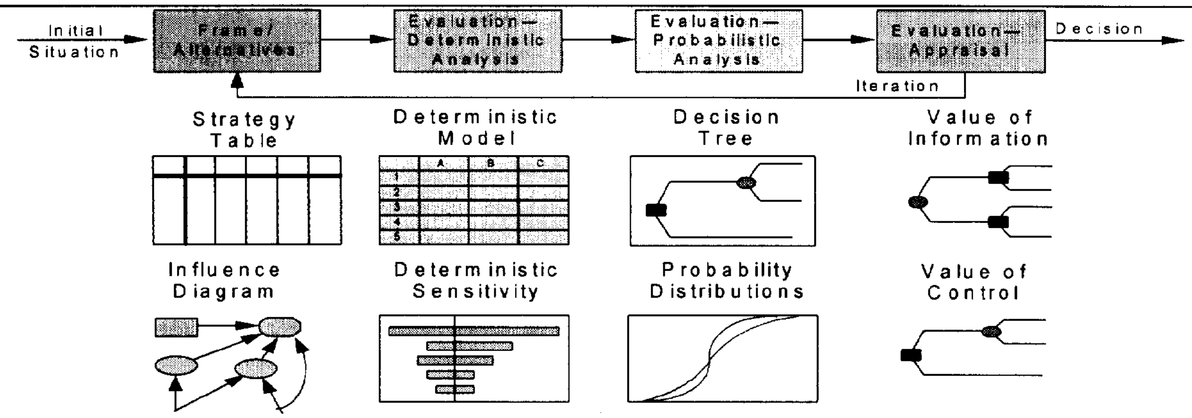

Figure 1 - Decision Risk Analysis Process

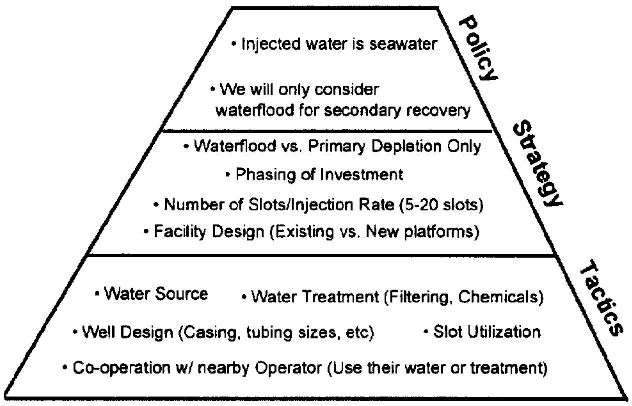

Figure 2 - Decision Hierarchy

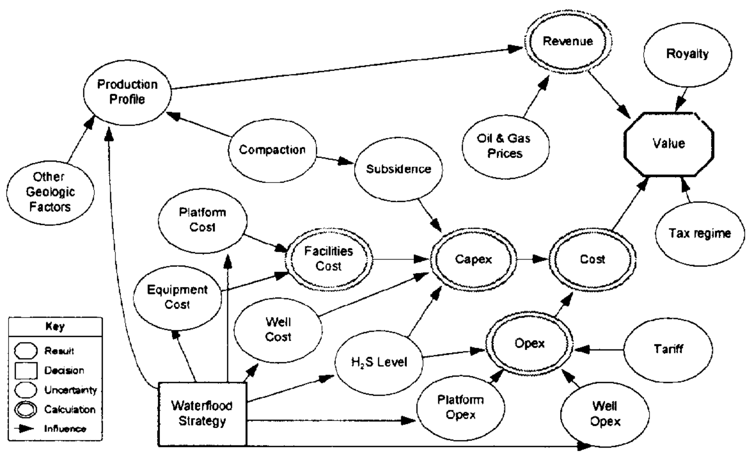

Figure 3 - Influence Diagram

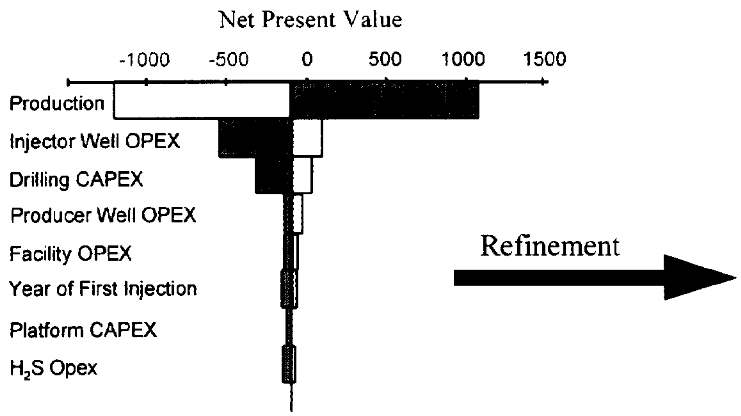

Figure 4a - Initial Project Tornado Chart

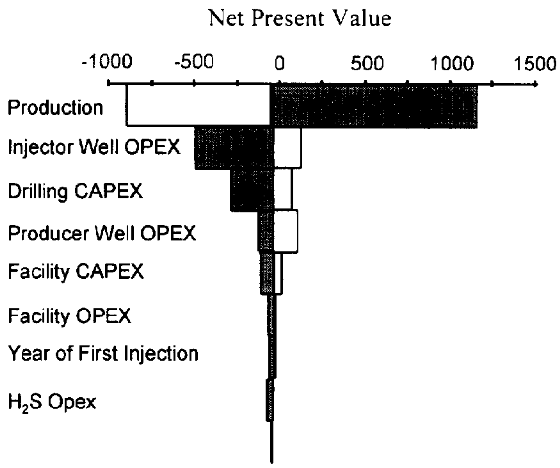

Figure 4b - Final Project Tornado Chart

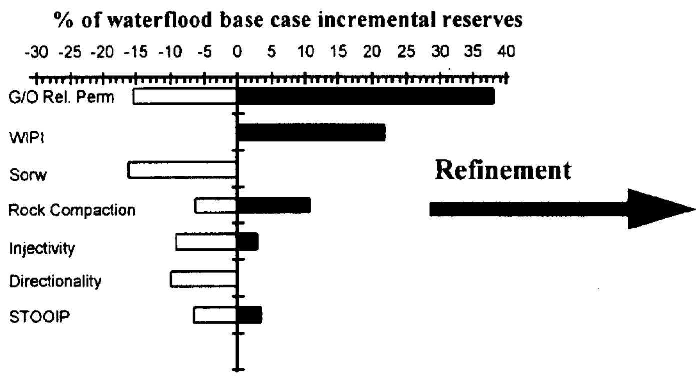

Figure 5a - Initial Production Tornado Chart

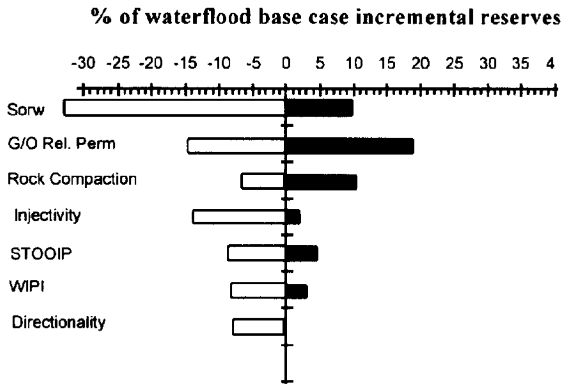

Figure 5b - Final Production Tornado Chart

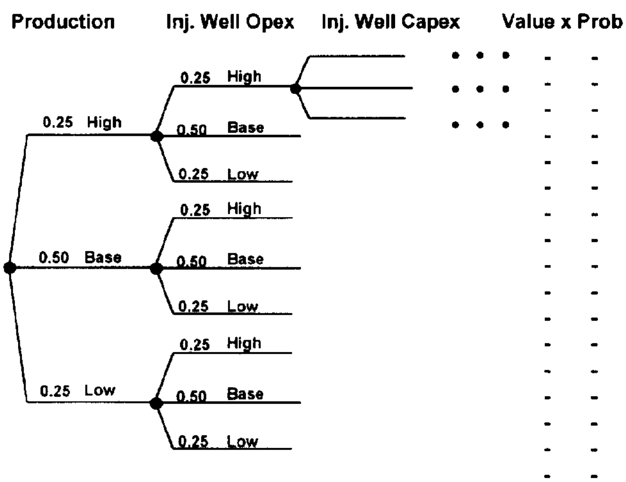

Figure 6 - Decision Tree Analysis

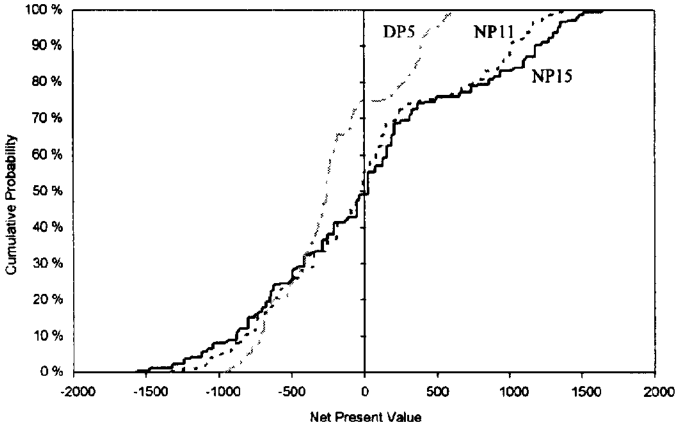

Figure 7 - Cumulative Probability Distribution - Comparison of Development Options

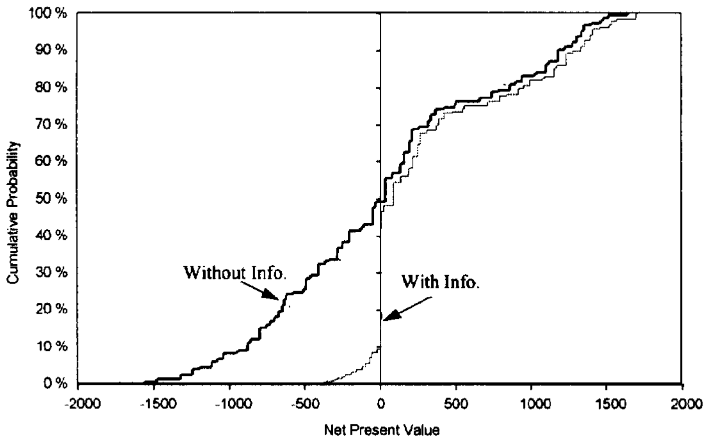

Figure 8 - Cumulative Probability Distributions - Value of information

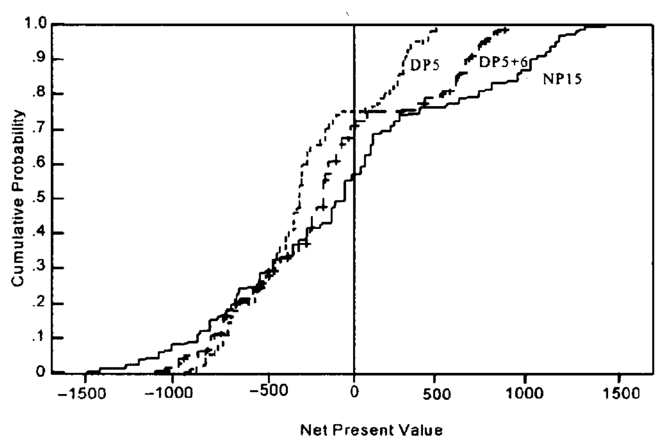

Figure 9 - Cumulative Probability Distributions - Effect of Phased Development